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LEPTON FLAVOR VIOLATING ERA OF NEUTRINO PHYSICS*

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The physics agenda for future long-baseline neutrino oscillation experiments is outlined and the prospects for accomplishing those goals at future neutrino facilities are considered. Neutrino factories can deliver better reach in the mixing and mass-squared parameters but conventional super-beams with large water or liquid argon detectors can probe regions of the parameter space that could prove to be interesting.

1 Introduction

Neutrino oscillation phenomena probe the fundamental properties of neutrinos.[1] We presently have evidence for (i) atmospheric ν_μ disappearance oscillations with mass-squared difference $\delta m^2_{\rm atm} \approx 3 \times 10^{-3}\,{\rm eV}^2$, (ii) solar ν_e disappearance oscillations with $\delta m^2_{\rm solar} \approx 5 \times 10^{-5}\,{\rm eV}^2$, and (iii) and accelerator $\bar\nu_\mu \leftrightarrow \bar\nu_e$ and $\nu_\mu \leftrightarrow \nu_e$ oscillations with $\delta m^2_{\rm LSND} \approx 1$ eV^2. Limits from accelerator and reactor experiments place important constraints on oscillation possibilities. In particular, reactor experiments exclude large amplitude $\bar\nu_e$ disappearance oscillations at $\delta m^2 > 10^{-3}\,{\rm eV}^2$.

A 3-neutrino model can explain the atmospheric and solar data and provides a useful benchmark for neutrino factory studies. The mixing of 3 neutrinos can be parametrized by 3 angles ($\theta_{23},\ \theta_{12},\ \theta_{13}$) and a CP-violation phase (δ). The angle θ_{23} controls the atmospheric oscillation amplitude, θ_{12} controls the solar oscillation amplitude, and θ_{13} couples atmospheric and solar oscillations and controls the amount of ν_e oscillations to ν_μ and ν_τ at the atmospheric scale.

What we now know from experiments is that:

(i) $\theta_{23} \sim \pi/4\,,\ \left|\delta m^2_{32}\right| \sim 3\times10^{-3}\,{\rm eV}^2$ for atmospheric oscillations;

(ii) $\theta_{12} \sim \pi/4\,,\ \left|\delta m^2_{32}\right| \sim 5\times10^{-5}\,{\rm eV}^2$ is favored for solar oscillations (the LAM solution) but other values are not fully excluded;

(iii) $\theta_{13} \sim 0$ ($\sin^2 2\theta_{13} < 0.1$) from the reactor experiments.

In the limit $\theta_{13} = 0$, the oscillations are bimaximal.[2]

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A new round of accelerator experiments with medium baselines is under way.[3] The K2K experiment ($L = 250$ km, $\langle E_\nu \rangle \sim 1.4$ GeV) is finding evidence in line with the atmospheric ν_μ disappearance. The MINOS experiment ($L = 730$ km, $\langle E_\nu \rangle \sim 10$ GeV) and the CNGS experiments ICANOE and OPERA ($L = 730$ km, $\langle E_\nu \rangle \sim 20$ GeV) are expected to "see" the first oscillation minimum in $\nu_\mu \leftrightarrow \nu_\mu$, measure $\sin^2 2\theta_{23}$ to 5% and $\delta m^2_{\rm atm}$ to 10% accuracy, and search for $\nu_\mu \to \nu_e$ down to 1% in amplitude. The short-baseline MiniBooNE experiment at Fermilab will confirm or reject the LSND effect.[4] However, information about neutrino masses and mixing will still be incomplete. Higher intensity beams of both ν_μ and ν_e flavors are needed.

Conventional neutrino beams based on π, K decays are dominantly ν_μ and $\bar\nu_\mu$. Neutrino factories would provide high intensity ν_μ and $\bar\nu_e$ (or $\bar\nu_\mu$ and ν_e) beams from muon decays. The ν_e and $\bar\nu_e$ beams would access neutrino oscillation channels that are otherwise inaccessible and are essential for eventual reconstruction of the neutrino mixing matrix.

2 Neutrino Factory

Collimated high-intensity neutrino beams can be obtained from decays of muons stored in an oval ring with straight sections.[5] For $\mu^- \to \nu_\mu e^- \bar\nu_e$ decays, the oscillation channels $\nu_\mu \to \nu_\mu$ (disappearance), $\nu_\mu \to \nu_e$ (appearance), and $\nu_\mu \to \nu_\tau$ (appearance) give "right-sign" leptons μ^-, e^-, and τ^-, respectively, whereas the oscillation channels $\bar\nu_e \to \bar\nu_e$ (disappearance), $\bar\nu_e \to \bar\nu_\mu$ (appearance), and $\bar\nu_e \to \bar\nu_\tau$ (appearance) give "wrong-sign" leptons e^+, μ^+, and τ^+, respectively. The oscillation signals are relatively background free. The charge-conjugate channels can be studied in μ^+ decays.

With stored muon energies $E_\mu \gg m_\mu$, the neutrino beam is highly collimated and its flux is $\Phi \simeq N(E_\mu/m_\mu)^2/(\pi L^2)$, where N is the number of useful muon decays and L is the baseline. The νN cross section rises linearly with E_ν and hence with E_μ. The event rate is proportional to $(E_\mu)^3$. The $\bar\nu N$ cross section is about 1/2 of the νN cross section. The charged-current cross section for $\nu_\tau N$ suffers from kinematic suppression at low neutrino energies.

Muons are the easiest to detect. The sign of the muon needs to be measured to distinguish $\nu_\mu \to \nu_\mu$ (right-sign μ) and $\bar\nu_e \to \bar\nu_\mu$ (wrong-sign μ). The backgrounds to the wrong-sign signal are expected to be small if the energy of the detected μ is $\gtrsim 4$ GeV, which requires stored muon energies $E_\mu \gtrsim 20$ GeV. The sign of electrons is more difficult to determine. It might only be possible to measure the combined $\nu_\mu \to \nu_e$ and $\bar\nu_e \to \bar\nu_e$ events. Tau-leptons can be detected kinematically or by kinks. The τ-production threshold of $E_\nu = 3.5$ GeV requires higher energy neutrino beams.

The critical parameters of neutrino factory experiments are the number of useful muon decays N, the baseline L, and the data sample size (kt-years), where the latter is defined as the product of the detector fiducial mass, the efficiency of the signal selection requirements, and the number of years of data taking. An entry-level machine may have $N = 6 \times 10^{19}$ and $E_\mu = 20$ GeV, while a high-performance machine may have $N = 6 \times 10^{20}$ and $E_\mu =$ 35–70 GeV. The average neutrino beam energies are related to the stored muon energies by $\langle E_{\nu_\mu} \rangle = 0.7 E_\mu$ and $\langle E_{\nu_e} \rangle = 0.6 E_\mu$. Baseline distances from 730 km to 10,000 km are under consideration. For an iron scintillator target a detector mass of 10–50 kt may be employed. With these factories, thousands of neutrino events per year could be realized in a 10 kt detector anywhere on Earth. A number of recent studies have addressed the potential of long-baseline experiments to determine the neutrino masses and mixing parameters[6−14].

3 Physics Agenda (PA)

There is a well-defined set of physics goals for long-baseline neutrino experiments, as follows.

PA1: The measurement of θ_{13} is a primary goal. A nonzero value of θ_{13} is essential for CP violation and for matter effects with electron-neutrinos. The flavor-changing vacuum probabilities in the leading-oscillation approximation are

$$P(\nu_e \to \nu_\mu) \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left(\frac{\delta m^2_{\rm atm} L}{4E} \right) , \tag{1}$$

$$P(\nu_e \to \nu_\tau) \simeq \sin^2 2\theta_{13} \cos^2 \theta_{23} \sin^2 \left(\frac{\delta m^2_{\rm atm} L}{4E} \right) , \tag{2}$$

$$P(\nu_\mu \to \nu_\tau) \simeq \cos^4 \theta_{13} \sin^2 2\theta_{23} \sin^2 \left(\frac{\delta m^2_{\rm atm} L}{4E} \right) . \tag{3}$$

The $\nu_e \to \nu_\mu$ and $\nu_e \to \nu_\tau$ appearance channels provide good sensitivity to θ_{13}; including the disappearance channels improves the sensitivity. All baselines are okay for a θ_{13} measurement.

PA2: The sign of δm^2_{32} determines the pattern of neutrino masses (i.e., whether the closely spaced mass-eigenstates that give $\delta m^2_{\rm solar}$ lie above or below the third mass-eigenstate). The coherent scattering of electron neutrinos in matter gives a probability difference $P(\nu_e \to \nu_\mu) - P(\bar\nu_e \to \bar\nu_\mu)$ that is positive for $\delta m^2_{32} > 0$ and negative for $\delta m^2_{32} < 0$. At baselines of about 2000 km or longer, a proof in principle has been given that the sign of δm^2_{32} can be determined in this way at energies $E_\nu \sim 15$ GeV or higher.[6] A complicating factor is that fake CP violation from matter effects must be distinguished from intrinsic CP violation due to the phase δ.

In the presence of matter the $\nu_e \to \nu_\mu$ probability at small θ_{13} is approximately given by[6]

$$\langle P(\nu_e \to \nu_\mu) \rangle \simeq \frac{\sin^2 2\theta_{13}}{\left|1 - \frac{\langle A \rangle}{\delta m^2_{32}}\right|} \sin^2 \left\{ 1.27 \frac{\delta m^2_{32} L}{\langle E_\nu \rangle} \left| 1 - \frac{\langle A \rangle}{\delta m^2_{32}} \right| \right\} , \qquad (4)$$

where $\langle A \rangle = 2\sqrt{2}\, G_F \langle N_e \rangle \langle E_\nu \rangle$. The sign of A is reversed for $\bar{\nu}_e \to \bar{\nu}_\mu$. Matter effects can enhance appearance rates by an order of magnitude at long baselines. One appearance channel is enhanced and the other suppressed so the separation of the $\nu_e \to \nu_\mu$ and $\bar{\nu}_e \to \bar{\nu}_\mu$ probabilities turns on as L increases.

PA3: Precision measurements of the leading-oscillation parameters at the few percent level are important for testing theoretical models of masses and mixing. The magnitude of δm^2_{32} affects the shape of the oscillation suppression and $\sin^2 2\theta_{23}$ affects the amount of suppression, so both can be well measured by neutrino factories.

PA4: The subleading $\delta m^2_{\rm solar}$ oscillation can be probed if the currently favored large-angle mixing (LAM) solution to the solar neutrino problem proves correct. The KAMLAND reactor $\bar{\nu}_e$ experiment should also accurately measure the subleading-oscillation parameters of the LAM solution.[15]

PA5: An important goal of neutrino factories is to detect intrinsic CP violation, $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$. This is only possible if the solar solution is LAM. Sensitivity to intrinsic CP violation is best for baselines $L = 2000$–4000 km. Intrinsic CP violation at a neutrino factory dominates matter effects for small θ_{13} ($\sim 10^{-4}$), whereas matter effects dominate intrinsic CP for large θ_{13} ($\sim 10^{-1}$).

4 Conventional Neutrino SuperBeams

Conventional neutrino beams are produced from decays of charged pions. These beams of muon-neutrinos have small components of electron-neutrinos. Possible upgrades of existing proton drivers to megawatt (MW) scale are being considered to produce conventional neutrino superbeams.[16] An upgrade to 4 MW of the 0.77 MW beam at the 50 GeV proton synchrotron of the proposed Japan Hadron Facility (JHF) would give an intense neutrino superbeam (SuperJHF) of energy $E_\nu \sim 1$ GeV. An upgrade of the 0.4 MW proton driver at Fermilab would increase the intensity of the NuMI beam by a factor of four (SuperNuMI) with three options for the peak neutrino energy [E_ν(peak) ~ 3 GeV (LE), 7 GeV (ME), and 15 GeV (HE)]. The capabilities of these conventional superbeams to accomplish parts of the neutrino oscillation physics agenda are curently being explored.[16,17] Very large water detectors or smaller liquid argon detectors with excellent background rejection would be used in conjunction with the superbeams.

5 Physics Reach

The results in this section summarize a recent comparative study[17] of superbeam and neutrino-factory physics capabilities in future medium- and long-baseline experiments. The reach of various superbeam and neutrino factory options are compared in Table 1. In these results 3 years of neutrino running followed by 6 years of anti-neutrino running is assumed. For superbeams the argon detector (A) has 30 kt fiducial mass and the water detector (W) a 220 kt fiducial mass, a factor of 10 larger than SuperKamiokande; signal efficiency and estimated detector backgrounds are taken into account. For neutrino factories a 50 kt iron scintillator detector is assumed.

The $\sin^2 2\theta_{13}$ reach at neutrino factories depends on the subleading scale δm^2_{21}. This dependence is illustrated in Fig. 1 for stored muon energies of 20, 30, 40 and 50 GeV.

The sign(δm^2_{32}) and CP sensitivities are illustrated in Figures 2–5 for various neutrino beam and detector choices:

(i) neutrino factory with $E_\mu = 20$ GeV and $L = 2900$ km (Fig. 2);

(ii) SJHF with a water Cherenkov detector at $L = 295$ km (Fig. 3);

(iii) SNuMI with an E_ν(peak) ~ 3 GeV beam and a liquid argon detector at $L = 730$ km (Fig. 4);

(iv) SNuMI with an E_ν(peak) ~ 15 GeV beam and a liquid argon detector at $L = 2900$ km (Fig. 5).

In these SNuMI examples, the CP sensitivity is better in (iii) and the sign(δm^2_{32}) sensitivity is better in (iv).

The conclusions from our comparative study of neutrino factories and conventional superbeams are as follows:

(i) A neutrino factory can deliver between one and two orders of magnitude better reach in $\sin^2 2\theta_{13}$ for $\nu_e \to \nu_\mu$ appearance, the sign of δm^2_{32}, and CP violation. At an $L = 3000$ km baseline there is excellent sensitivity to all three observables. The $\sin^2 2\theta_{13}$ reach is below 10^{-4}. The sign of δm^2_{32} can be determined and a detection of maximal CP violation made if $\sin^2 2\theta_{13}$ is larger that 10^{-3}.

Table 1: Summary of the $\sin^2 2\theta_{13}$ reach (in units of 10^{-3}) for various combinations of neutrino beam, distance, and detector for (i) a 3σ $\nu_\mu \to \nu_e$ appearance with $\delta m^2_{21} = 10^{-5}$ eV^2, (ii) an unambiguous 3σ determination of the sign of δm^2_{32} with $\delta m^2_{21} = 5 \times 10^{-5}$ eV^2 , and (iii) a 3σ discovery of CP violation for $\delta m^2_{21} = 5 \times 10^{-5}$, 1×10^{-4}, and 2×10^{-4} eV^2, from left to right respectively. Dashes in the sign of δm^2_{32} column indicate that the sign is not always determinable. Dashes in the CPV columns indicate CPV cannot be established for $\sin^2 2\theta_{13} \leq 0.1$, the current experimental upper limit, for any values of the other parameters. The CPV entries are calculated assuming the value of δ that gives the maximal disparity of $N(e^+)$ and $N(e^-)$; for other values of δ, CP violation may not be measurable.

			$\sin^2 2\theta_{13}$ reach (in units of 10^{-3})				
Beam	L (km)	Detector	(i)	(ii)	(iii)		
JHF	295	A	25	–	–	–	25
		W	17	–	–	40	8
SJHF	295	A	8	–	–	5	3
		W	15	–	100	20	5
SNuMI LE	730	A	7	–	100	20	4
		W	30	–	–	–	40
SNuMI ME	2900	A	3	6	–	–	100
		W	8	15	–	–	–
	7300	A	6	6	–	–	–
		W	3	3	–	–	–
SNuMI HE	2900	A	3	7	–	100	20
		W	10	15	–	–	–
	7300	A	4	4	–	–	–
		W	3	3	–	–	–
20 GeV NuF	2900	50 kt	0.5	2.5	–	2	1.5
1.8×10^{20} μ^+	7300		0.5	0.3	–	–	–
20 GeV NuF	2900	50 kt	0.1	1.2	0.6	0.4	0.6
1.8×10^{21} μ^+	7300		0.07	0.1	–	–	–

(ii) Superbeams with a sufficiently ambitious detector can probe $\sin^2 2\theta_{13}$ down to a few $\times\, 10^{-3}$. Maximal CP violation may be detected with a JHF or SJHF beam ($E_\nu \sim 1$ GeV) at short baselines, but these facilities will have little sensitivity to sign(δm^2_{32}). Higher-energy superbeams could determine sign(δm^2_{32}) but have little sensitivity to CP violation.

6 Short Baselines

If the LSND effect in $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations is confirmed by MiniBooNE, then an optimal baseline for future CP-violation studies with a neu-

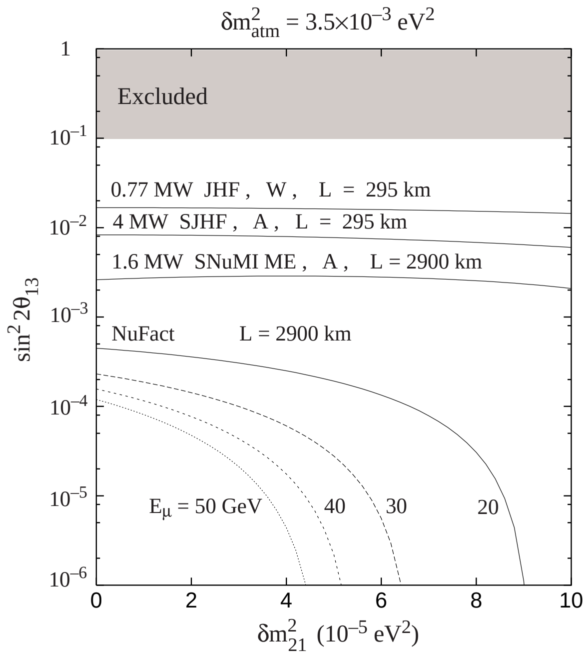

Figure 1: Limiting $\sin^2 2\theta_{13}$ sensitivity for the observation of $\nu_\mu \to \nu_e$ oscillations expected with superbeams and neutrino factories versus the subleading scale δm^2_{21}. (Adapted from the study in Ref. 17.)

trino factory would be

$$L \approx 45 \text{ km} \left(\frac{0.3 \text{ eV}^2}{\delta m^2_{\rm LSND}} \right) \left(\frac{E_\mu}{20 \text{ GeV}} \right) . \tag{5}$$

The distance from Fermilab to Argonne is 30 km, for example. In four-neutrino oscillations, which would be indicated if the LSND, atmospheric, and solar effects are all due to neutrino oscillations, there are 3 CP-violating phases. The size of CP-violating effects in $\nu_e \to \nu_\mu$ and $\nu_\mu \to \nu_\tau$ may be enhanced or reduced relative to three-neutrino oscillations.

7 Overview

We briefly sum up our conclusions regarding future neutrino factory and conventional superbeam studies of neutrino oscillations:

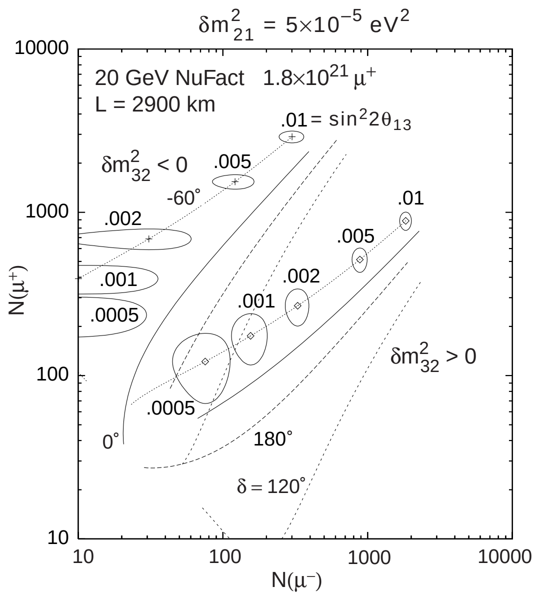

Figure 2: 3σ error ellipses in the $\left[N(\mu^+), N(\mu^-)\right]$-plane, shown for a neutrino factory delivering 3.6×10^{21} useful decays of 20 GeV muons and 1.8×10^{21} useful decays of 20 GeV antimuons, with a 50 kt detector at $L = 2900$ km, for $\delta m^2_{21} = 5 \times 10^{-5}$ eV^2. The solid and long-dashed curves correspond to the CP-conserving cases $\delta = 0°$ and $180°$, respectively, and the short-dashed and dotted curves correspond to two other cases that give the largest deviation from the CP-conserving curves; along these curves $\sin^2 2\theta_{13}$ varies from 0.0001 to 0.01, as indicated. (From Ref. 17.)

- Three-neutrino mixing and δm^2 parameters can be measured at neutrino factories.
- The amplitude $\sin^2 2\theta_{13}$ is the most crucial parameter. It can be measured down to 10^{-4} at a neutrino factory or to 3×10^{-3} with superbeams.
- A baseline $L \sim 3000$ km is ideal for neutrino factory measurements of sign(δm^2_{32}), CP violation, and the subleading δm^2_{21} oscillations.
- A longer baseline, $L \sim 7300$ km, is best for precision on δm^2_{32} and $\sin^2 2\theta_{32}$ at a neutrino factory; for superbeam measurements of $\sin^2 2\theta_{13}$ baselines of 3000–7000 km do equally well.
- Measurements at two baselines would provide complementary advantages (2800 and 7300 for neutrino factories or 295 km and 3000-7000 km for superbeams).

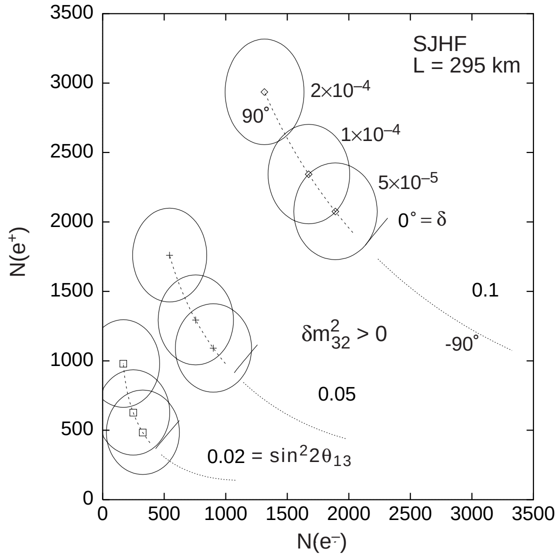

Figure 3: 3σ error ellipses in the $\left[N(e^+), N(e^-)\right]$-plane, shown for the 4 MW SJHF scenario with $L = 295$ km. The contours are for the water Cherenkov detector scenario, with $\sin^2 2\theta_{13} = 0.02$, 0.05, and 0.1. The solid (dashed) [dotted] curves correspond to $\delta = 0^\circ$ (90°) [-90°] with δm^2_{21} varying from 2×10^{-5} eV^2 to 2×10^{-4} eV^2. The error ellipses are shown for three simulated data points at $\delta m^2_{21} = 5 \times 10^{-5}$, 10^{-4} and 2×10^{-4} eV^2. (From Ref. 17.)

- With the LAM solar solution, intrinsic CP-violating effects could be observable at SuperJHF and at a neutrino factory. The false CP-violation from matter is a serious but manageable complication at long baselines. Further studies are needed to determine the range of δ for which CP-violating effects are measurable.

- For four-neutrino oscillations, short baselines ($L \sim$ 5–50 km) are also important. With four neutrinos, CP violation occurs at the $\delta m^2_{\rm atm}$ scale and large effects may be seen.

- Superbeams may be a reasonable next step in exploration of the neutrino sector. However, neutrino factories will eventually be needed for a complete understanding of the neutrino flavor-changing transitions.

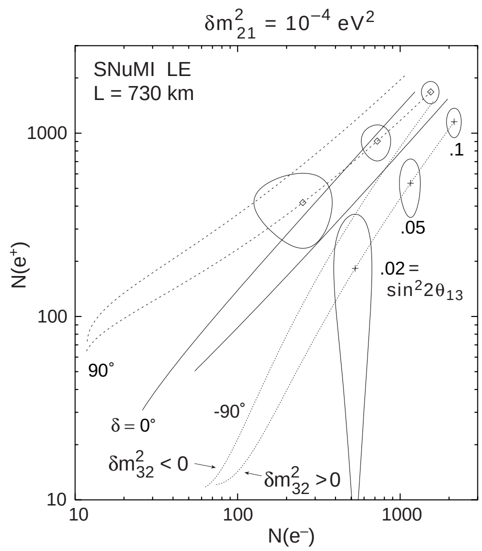

Figure 4: 3σ error ellipses in the $\left[N(e^+), N(e^-)\right]$-plane, shown for the liquid argon detector scenario with the upgraded LE SNuMI beam at $L = 730$ km. The contours are for $\delta m^2_{21} = 10^{-4}$ eV^2. The solid and long-dashed curves correspond to the CP-conserving cases $\delta = 0°$ and $180°$, respectively, and the short-dashed and dotted curves correspond to two other cases that give the largest deviation from the CP-conserving curves; along these curves $\sin^2 2\theta_{13}$ varies from 0.001 to 0.1, as indicated. (From Ref. 17.)

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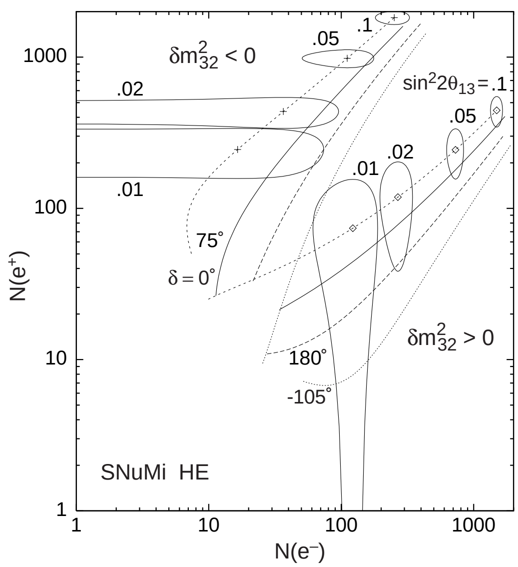

Figure 5: 3σ error ellipses in the $\left[N(e^+), N(e^-)\right]$-plane, shown for the liquid argon detector scenario at $L = 2900$ km with the upgraded HE SNuMI beam. The contours are for $\delta m^2_{21} = 10^{-4}$ eV^2. The solid and long-dashed curves correspond to the CP-conserving cases $\delta = 0°$ and $180°$, respectively, and the short-dashed and dotted curves correspond to two other cases that give the largest deviation from the CP-conserving curves; along these curves $\sin^2 2\theta_{13}$ varies from 0.001 to 0.1, as indicated. (From Ref. 17.)

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